Table 2. COLOUR INDICES

	U–B	B–V
Primary pulse	-0.38	0.52
Secondary pulse	-0.50	0.60

the two pulses is not considered significant. Our present tie-in with the UBV system is somewhat tenuous.

The measured V magnitude of the primary pulse, averaged over the 1·3 ms duration of the pulse, is 14·4, and that of the secondary pulse is 15·8. The V magnitude of the sum of the two pulses, averaged over a complete pulsation cycle of 33·095 ms, is 17·4. It will be interesting to see if the object maintains this average brightness.

For an assumed distance to the Crab Nebula of 2·02 kpc (ref. 5), and with an interstellar absorption $A_v = 1.1$ magnitudes (ref. 6), our measured V magnitude during the primary pulse corresponds to an absolute magnitude $M_v = +1.8$. Our measured colours for the primary pulse, corrected for interstellar reddening[6], are U–$B = -0.66$ and B–$V = 0.15$. Using the absolute calibration of the UBV system given by Johnson[7], we can compare the flux in the optical region with the value for the pulse energy at 112·5 MHz given by Staelin and Reifenstein[1]. For an assumed synchrotron-type emission power law $I(\nu) \propto \nu^{-n}$ this comparison gives $n = 0.69$. The UBV colours predicted from such an energy distribution (U–$B = -0.80$, B–$V = +0.23$ (ref. 8)) are in reasonable agreement with our observed colours. We conclude that the pulsar radiation can be interpreted as synchrotron radiation.

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Nature of Radio and Optical Emissions from Pulsars

by

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A report of how rotating and oscillating magnetic neutron stars can account for the radio and optical signals from pulsars. Several predictions of the nature of the signals are put forward.

IN several papers[1–3] and some unpublished work we have shown that radio emissions from rotating magnetic neutron stars with surface field strengths of $\sim 10^8$ gauss and surface temperatures of $\sim 10^5$ °K can explain the observed pulsed radio emission of pulsars[4]. We have also pointed out that certain line emissions at frequencies well above 10^{12} Hz are expected[1]. Recently, Cocke, Disney and Taylor (ref. 5 and page 525 of this issue) have discovered that the pulsar NP 0532 (in the Crab Nebula) emits optical pulses of width ~ 4 ms and repetition period equal to that of the radio pulses. In this article we show that the theory for ultraviolet line emissions already advanced by us can also account for the optical pulses observed by Cocke *et al.*

In a magnetic field the electrons move in circular orbits the radius (the Larmor radius) of which is determined by the field strength and the electron energy. When the Larmor radius of an electron approaches the de Broglie wavelength, however, the energy of the electron in the plane perpendicular to the field H (taken to be in the z-direction) is quantized and the classical theory of magnetohydrodynamics breaks down. The non-relativistic expression for the quantized electron energy is[6]

$$E = \tfrac{1}{2}\,(p_z^2/m) + 1.16\, M\, H_8\ (\mathrm{eV}) \qquad (1)$$

where p_z is the z-momentum of the electron (the motion of the electron in the direction of the field is unaffected by this quantization) and M is a quantum number taking integral values from 0 to ∞. (M describes the size of the electron orbit and the direction of the spin.) H_8 is the magnetic field in units of 10^8 gauss. For $H_8 = 1$, and a temperature of 10^5 °K, most electrons are in states of lowest quantum number.

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There are only two radiation processes:

(1) *Electron bremsstrahlung.* An electron can make a transition in the same quantum state by decreasing its value of p_z. This is accomplished by collisions with a nucleus

$$e^- + (Z,A) \xrightarrow{\text{magnetic field}} e^- + (Z,A) + h\nu \qquad (2)$$

This is similar to the classical bremsstrahlung process (free–free transition) but here the electrons move in quantized orbits. These electrons are one-dimensional particles.

(2) *Quantized synchrotron radiation.* Classically an electron can emit radiation of arbitrary wavelength by spiralling into orbits of smaller diameters (synchrotron radiation). In the quantized orbits, the electrons can only make discrete transitions from a state M to another M' ($M - M' = \Delta M > 0$), emitting a photon of energy ΔM 1·16 H_8 eV. If the magnetic field is not homogeneous, for example, varying by a factor of two over the emitting region, then these discrete lines will be smeared out into a continuous spectrum. This type of transition is analogous to the classical bound–bound transition.

There is no analogy to the classical bound–free transition in a magnetic field.

The brightness temperatures of radio and optical emissions from pulsars are considerably greater than 10^7 °K. It is known that the energy emitted by a gas in thermal equilibrium cannot exceed that given by the Planck law. Both the radio and optical emissions must therefore be produced by non-equilibrium processes. A non-equilibrium process can give rise to high intensity radiation when the population of particles in an energy level higher than the ground state is greater than the equilibrium value.

This is called population inversion. In pulsars a process must therefore exist by which level inversion is maintained over a long time scale.

We now show that such departures from thermodynamic equilibrium can take place when the magnetic neutron star oscillates in the direction of the field. During an oscillation, the temperatures of electrons and ions will change adiabatically. The ions are classical particles, so their temperatures will change according to the classical adiabatic law for an ideal gas, that is, $T_i \propto \rho^{2/3}$ where T_i is the temperature of the ions and ρ is the density. In an intense field, however, the electrons become one-dimensional particles[6]. If they undergo an adiabatic process and do not change their quantum number (the case when they change their quantum numbers will be discussed later), then their temperature changes according to the adiabatic law for a one-dimensional gas, that is, $T_e \propto \rho^2$ where T_e is the electron temperature. If the electrons are initially in equilibrium with the ions, then during the expansion phase of the oscillation the electrons will become cooler than the ions. The upper magnetic states will then be overpopulated, and a population inversion will be set up. Stimulated emission can cause electrons in the upper states to avalanche into states of lower quantum numbers, in a laser-like process with a very high energy flux. The energy of photons will be in multiples of $1 \cdot 16\ \Delta M\ H_8$ eV, but transitions with lower values of ΔM will be favoured.

In the contracting phase of oscillation, matter moves back to regions of higher density. Then the reverse occurs. Because of the difference in their adiabatic laws, the electrons will acquire a higher temperature than the ions. In order to achieve equilibrium, part of the electrons may return to the upper state, but some electrons will only lose energy via the electron bremsstrahlung process. Because the electrons are not in thermal equilibrium, energy is produced at a rate governed only by the absorption process. This gives rise to the radio emission, which may be coherent.

We have computed the emissivity of the electron bremsstrahlung and quantized synchrotron radiation. The spectrum and radiation rate of electron bremsstrahlung in the $M=0$ state is given by the following equation[2]

$$I = 3 \cdot 01 \times 10^{-29}\ N_i N_e H_8\ Z^2\ E_5^{5/2}\ \nu_8^{-2}\ \text{erg s}^{-1}\ \text{cm}^{-3}\ (10^8\ \text{Hz})^{-1} \quad (3)$$

where N_e and N_i are electron and ion number densities respectively, Z is the charge of the nucleus, E_5 is the electron energy measured in $k \cdot 10^5$ °K$=8 \cdot 63$ eV, and ν_8 is the frequency of radiation in 10^8 Hz. The surface density of a neutron star is 1 g cm^{-3} and the corresponding particle density is about 10^{24} cm^{-3}. The scale height is about 1 cm at a temperature of 10^5 °K. If the oscillation involves matter up to a depth of several cm with an amplitude which is also a few cm, then a sizable fraction of electrons can become overheated in the contracting phase of the oscillation. If we assume an optical depth of a few cm (theoretically the absorption coefficient for radio waves vanishes along the field), we obtain a radio flux of about 10^{17} ergs cm^{-2} s^{-1}. If we assume a total radiating surface of 10 per cent of the neutron star area of 10^{13} cm^2, we find a flux of about 10^{29} erg s^{-1}, which is the same as the observed radio flux. Further, the spectral index of the radio radiation is -2, which is what is observed for most pulsars. The bremsstrahlung radiation is 100 per cent linearly polarized. Coherent processes discussed previously can cause the emitted radiation to have a 100 per cent overall polarization. This agrees with observation.

The optical radiation is produced by transitions among neighbouring magnetic states. We have computed the emission probability for all transitions[3]. In particular, for the $M=1$ to $M'=0$ transition, the result is

$$I_{1\to 0} = 2 \cdot 85 \times 10^{-5}\ N_e^M H_8^3\ (1+\cos^2\theta)\ \text{erg cm}^{-3}\ \text{s}^{-1}\ \text{ster}^{-1} \quad (4)$$

where N_e^M is the number density of electrons in the state M. N_e^M is also a sizable fraction of the electron density for the temperature and change of field strength considered. Applying equation (4) to the surface of neutron stars, we find that the surface flux of photons of energy equal to $1 \cdot 16\ H_8$ eV is about 10^{18} erg cm^{-2} s^{-1}. (The optical depth corresponding to the inverse process is about $0 \cdot 1$ cm at the neutron star surface density.) Again, assuming a total emitting area of 10^{12} cm^2 out of a total 10^{13} cm^2, we find that at a distance corresponding to that of the Crab Nebula this radiation is equivalent to that of a fifteenth magnitude star "turning on and off" (ref. 5 and page 525 of this issue). The emission in equation (4) is 100 per cent circularly polarized. We thus expect that the optical emission from pulsars will be nearly 100 per cent circularly polarized because of coherent processes.

The plasma frequency at the surface of a neutron star is about 10^{16} Hz, which is greater than that of the radio emission, and also that of the optical emission if the magnetic field is less than 4×10^{10} gauss. Then how can this radiation emerge? Along the field direction the radiation cannot interact with electrons (the electrons have no motion perpendicular to the magnetic field and hence cannot interact with the electric field component of the wave if the wave propagates along the magnetic field). This means that the radiation will not be absorbed and will be guided by the magnetic field lines from the pole region into a sharply defined beam. As the star rotates, this beam will sweep in space, giving rise to the observed pulsed radiation.

Thus we see that both the radio and the optical emissions have a common origin. The radio emission is caused by bremsstrahlung of electrons moving in the same magnetic quantized orbit, an analogy of one-dimensional bremsstrahlung. The optical emission is produced by electrons falling from orbits of high quantum number to lower quantum number, but the transition favours adjacent transitions. "Line" emissions of energy $1 \cdot 16\ H_8$ eV will be produced, but the line character of this radiation is smeared out by large scale inhomogeneities of the field. The radio and the optical emissions take place in the outgoing and ingoing halves of the stellar oscillations respectively. Thus we expect the general pulse shape of optical and radio emissions to be the same. We also expect, however, that the optical and the radio emissions will have opposite phases in the submillisecond oscillations of each pulse. Observations (discussed later) show that the radio and the optical emissions do have the same general pulse shape, indicating their common origin, but the optical observation has not been extended to detect submillisecond oscillations in each pulse, as needed to check this theory.

Another question remains: what is the driving mechanism of submillisecond oscillations in a neutron star? The ability to emit large pulses of radiation intermittently is equivalent to an opacity that can change drastically with time. Study of the structure of classical Cepheid variable stars shows that if the opacity changes rapidly with temperature and density, the star is unstable against oscillation. This type of process when applied to magnetic neutron stars will lead to an oscillation that is non-radial because the opacity is anisotropic. The amplitude of oscillation will extend only to outer regions where a thermal structure exists, and not to the deep interior. Both neutrino and gravitational wave losses will be quite negligible in this case.

Because a large oscillation amplitude is not required to pump electrons into high magnetic states or to produce superthermal electrons—an amplitude of a few cm is enough—we can expect that the wavelength of oscillation will be small. This means that the density waves will be quite irregular, just like waves in a sea. The emitted radiation can only travel along the line of force. The lines of force diverge from the surface into space at different angles, however. According to our theory, therefore, at any instant we will examine only a small portion of the surface. The wave structure of this small portion of surface then determines the character of emission. This is our explanation for the observation that the radio pulses contain random submillisecond structure. This can also produce successive pulses of very different intensities.

The wavelength of optical emission, according to our theory, depends on the magnetic field. Thus if an optical spectrum can be obtained that corresponds to a particular phase of the pulse, it will inform us about the magnetic structure at the surface of the star. (Unfortunately the spectrum of radio emission does not tell us about the magnetic field of the star. It tells us something about the magnetic field in the form of a convolute integral.) Lines corresponding to quantized synchrotron emission may also exist in these "flash spectra".

If the field strength exceeds a few times 10^8 gauss, the radiation will be in the ultraviolet band, and may be very hard to detect. Likewise, if the field strength is below 10^8 gauss, most of the radiation will be in the infrared. Thus we expect that optical pulses from pulsars will not be a frequent phenomenon unless it happens that fields of just about 10^8 gauss are common among pulsars. This may be the explanation why earlier work seeking optical radiation from some pulsars has been unsuccessful.

While we were writing this article one of us (H.-Y. C.) was invited by Dr Roger Lynds and Dr Stephen P. Maran to the dome of the 84 inch telescope of the Kitt Peak National Observatory to witness their identification[7] of the pulsar in the Crab Nebula which emits the pulsed light discovered by Cocke *et al.* earlier (ref. 5 and page 525 of this issue). It was the very star which Baade[8] and Minkowski[9] suggested in 1942 as the remnant of the supernova! The spectrum taken by Minkowski in 1942 with the Mt Wilson 100 inch telescope showed no lines nor any identifiable features, but, as Minkowski remarked, the spectrum was definitely not that of a black body. The spectrum obtained by Lynds (private communication) also showed no identifiable features. The peak of the spectrum is at about 5800 Å. If all the radiation in this spectrum comes from magnetic transitions, then the magnetic field strength at the surface of the Crab Nebula is about 2×10^8 gauss. (A magnetic neutron star can also radiate thermally, but the energy of the photons radiated must exceed h times the plasma frequency, or 50 eV. A substantial amount of energy can be emitted if the temperature exceeds 5×10^5 °K. This radiation is of the order of 10^{31} ergs s^{-1} if the temperature is 10^6 °K. This radiation can be converted into visible light by surrounding matter.)

Lynds and Maran also obtained the macroscopic structure of the pulses, which they found resemble those of the radio emission, and consist of two components, the weaker appearing about 14 ms after the main pulse. According to our theory, the second pulse is produced by the pole opposing the pole giving rise to the main pulse. The time asymmetry of the two pulses within one pulse period shows that the magnetic moment of the neutron star is off-set from the centre, and very likely inclined at a large angle to the axis of rotation.

In conclusion, we believe that we have found a rational explanation of the optical and radio pulses from pulsars. The pulsars are rotating and oscillating magnetic neutron stars. Both the optical and radio radiations are produced by electrons moving in quantized orbits in very intense magnetic fields. Both optical and radio emission will have the same pulse shape. This agrees with observation[7]. We predict, however, that the optical and the radio emission will have opposite phases in the submillisecond oscillatory structure of each pulse. The energy source for both radiations is the residual thermal energy of the neutron star and should last something like 10^7 yr. The radio spectral index is determined by detailed properties at the surface but should be in the neighbourhood of -2. The wavelength of optical emission is determined by the field strength and not by the surface temperature. Hence the wavelength at which the optical radiation (or infrared or ultraviolet) takes place is an indication of the field strength. The field strength of the pulsar in the Crab is thus determined to be 2×10^8 gauss.

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Neutral Hydrogen Asymmetry in the Galaxy *M*101 as Evidence for Tidal Effects

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Measurements of the distribution of neutral hydrogen in the galaxy M101 reveal an asymmetry which raises interesting points about tidal effects in galaxies due to nearby companions.

A recent 21 cm hydrogen line survey of the Sc galaxy *M*101 (*NGC* 5457) completed at Jodrell Bank using the Mark I radio telescope has shown an interesting asymmetry in its neutral hydrogen distribution. This can be seen in Fig. 1, which compares a contour map of the integrated neutral hydrogen with the main optical features of *M*101.

The most intense neutral hydrogen emission is found